ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Vision Research 47 (2007) 1790–1797
Vision Research
www.elsevier.com/locate/visres

The effects of the global structure of the mask in visual backward masking ☆

Frouke Hermens *, Michael H. Herzog

Laboratory of Psychophysics, Brain Mind Institute, École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

Received 8 November 2006; received in revised form 6 February 2007

Abstract

The visibility of a target can be strongly affected by a trailing mask. Research on visual backward masking has typically focused on the temporal characteristics of masking, whereas non-basic spatial aspects have received much less attention. However, recently, it has been demonstrated that the spatial layout is an important determinant of the strength of a mask. Here, we show that not only local but also global aspects of the mask's spatial layout affect target processing. Particularly, it is the regularity of the mask that plays an important role. Our findings are of importance for theoretical research, as well as for applications of visual masking.

Keywords: Visual perception; Backward masking; Mask structure; Regularity

1. Introduction

In visual backward masking, a briefly presented target is followed by a mask, which impairs performance on the target. Whereas several studies in simultaneous masking have investigated spatial layout effects, most research in backward masking has been devoted to the temporal aspects of masking, such as the duration of the target and the mask, or the time between their onsets (the stimulus onset asynchrony; SOA). Surprisingly, relatively few studies have investigated the effect of the spatial layout of the backward mask. When spatial aspects were studied, typically low-level aspects were investigated, such as the spatial distance between target and mask (e.g., Alpern, 1953; Growney, 1977) and the size of the stimuli (Bridgeman & Leff, 1979; Kolers, 1962; Sturr, Frumkes, & Veneruso, 1965; Sturr & Frumkes, 1968). There are a few notable exceptions (Ramachandran & Cobb, 1995; Wehrhahn, Li, & Westheimer, 1996; Werner, 1935; Williams & Weisstein, 1981, 1984) in which the importance of the objectness of the mask was demonstrated. It was not until recently that the effects of the spatial layout of the mask started to be investigated *systematically* (Herzog, Dependahl, Schmonsees, & Fahle, 2004; Herzog & Fahle, 2002; Herzog, Fahle, & Koch, 2001; Herzog et al., 2003). These studies showed that small changes in the mask's layout, such as adding two small contextual lines (Herzog, Schmonsees, & Fahle, 2003), can strongly change the mask's effect on the target. These large effects induced by relatively minor modifications to the layout are hard to explain with low-level stimulus descriptions, such as the overall intensity of the mask (luminance × surface × duration), or the distance between target and mask.

The above experiments made use of the shine-through effect (Herzog et al., 2001; Herzog & Fahle, 2002; Herzog & Koch, 2001). If a bright vernier target (two vertical segments with a small horizontal offset) is followed by an array of 25 aligned vertical verniers, both presented on a dark background, the vernier target is clearly visible. However, if two elements are removed from the array of verniers such that two gaps arise in the grating at the same

☆ We would like to thank Marc Repnow for technical support, Megi Sharikadze for assistance in the data collection of Experiment 1, and Peter van der Helm for his assistance with structural information theory. This work was funded by the Swiss National Science Foundation (SNF).
* Corresponding author.
E-mail address: frouke.hermens@epfl.ch (F. Hermens).

0042-6989/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2007.02.020

distance from the vernier target, masking becomes much stronger, and the preceding vernier is hardly visible. This is a surprising finding, because it shows that reducing the overall intensity of a mask can increase its masking strength.

The experiments with the shine-through effect have shown strong effects of the layout of the mask. However, all these effects were local in nature. For example, two lines were removed (Herzog et al., 2001) or two contextual lines were added to the mask (Herzog, Schmonsees et al., 2003). Here, we show that also the *global* spatial layout of the mask strongly affects its masking strength, by keeping the mask elements close to the target constant and varying the structure of the remainder of the mask. We found that masking was strongest when the mask elements were distributed in an irregular fashion, suggesting an important role of mask regularity in masking.

2. General materials and methods

2.1. Participants

The authors, members of the department, and undergraduate students participated in the experiments. The age of the participants ranged from 20 to 40 years. All participants had normal or corrected-to-normal vision, as determined by means of the Freiburg visal acuity test (Bach, 1996). Participants had to reach a value of at least 1.0 (corresponding to 20/20) in this test for at least one eye. The students were paid for their participation.

After being informed about the general purpose of the study, participants gave informed consent and were informed that they could quit the experiment at any time they wished. None of the participants used this possibility.

2.2. Apparatus

Stimuli were presented on an X–Y display (HP 1334 A or Tektronix 608) controlled by a PC (Pentium 4 or Power Macintosh) via fast 16 bit D/A converters (1 MHz pixel rate).

Depending on the target duration, which was selected individually for each participant, the refresh time of the display was set to 5 or 6 ms. The luminance of the stimuli was set to approximately 80 cd/m^2 as determined with a Minolta LS-100 luminance meter. A background light illuminated the room at about 0.5 lux.

2.3. Stimuli

In all experiments, the target stimulus consisted of a vertical vernier of which the segments were horizontally offset (as illustrated in the small inset of Fig. 1). Segments were 10′ long and separated by a small vertical gap of 1′. Hence, the total length of the vernier was 21′. The vernier duration was determined individually for each observer and ranged from 10 to 30 ms.

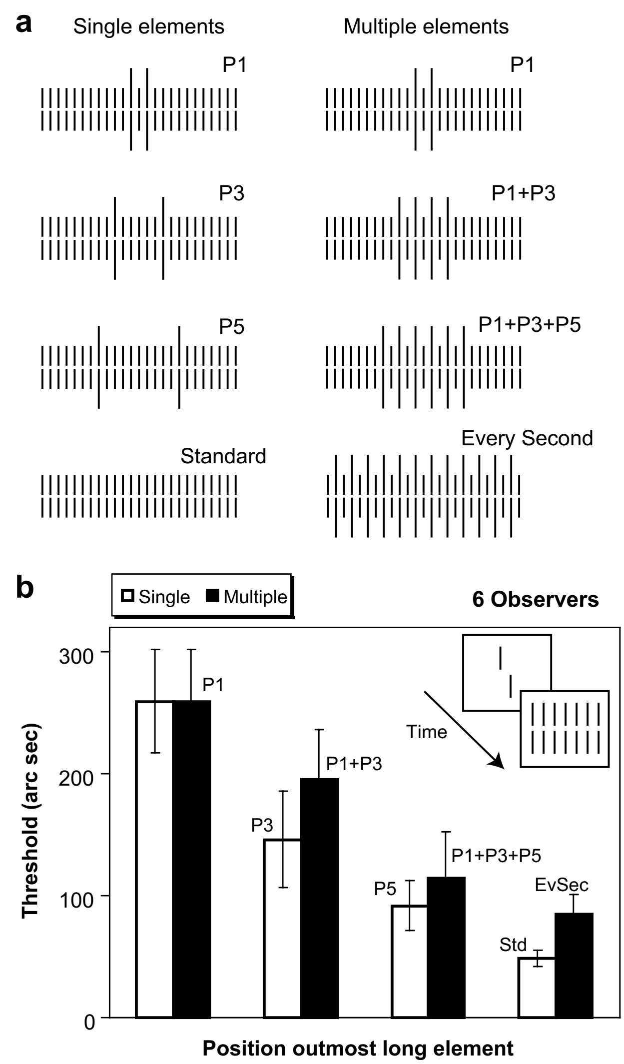

Fig. 1. Masks (a, in reverse contrast) and mean thresholds across observers (b) of Experiment 1. In the 'single element' conditions, we find that placing the longer lines further away from the center results in lower thresholds, indicating weaker masking (white bars). In the 'multiple elements' conditions, adding more lines to the mask resulted in a decrease of the threshold (black bars). Error bars show the standard error of the mean. The small inset in the data plot illustrates the sequence of target and mask (in reverse contrast).

A mask immediately followed the target vernier. The standard mask consisted of an array of 25 aligned verniers (see left of Fig. 1, 'Standard' grating). Additional grating masks were constructed from this standard grating by changing the length of some of the standard grating elements. The spacing between grating elements was 200″ in all conditions. Masks were presented for 300 ms.

The target vernier and the grating mask were both presented in the middle of the screen, and were preceded by a fixation screen consisting of a small cross in the center of the screen and four line elements in each of the corners for 1 s, followed by a blank screen presented for 400 ms.

2.4. Design

For all conditions, offset discrimination thresholds for the vernier target were determined twice in blocks of 80 trials. The order of presentation of the different masks within each experiment was varied randomly across participants (however, the standard mask was presented first to all participants). After participants were presented with all conditions once, a second run was performed for each condition. For this second run, the order of conditions was reversed for each observer to counteract effects of fatigue and practice in the averaged data. In the data analysis, we pooled the thresholds of the two blocks into one mean. The offset direction of the vernier target (left or right) was pseudo-randomized across trials, restricting the number of subsequent same offset directions to four.

2.5. Procedure

Observers were seated in a comfortable chair at a distance of two meters from the monitor. By means of two push buttons, participants indicated whether the bottom element of the target vernier was offset to the left or right with respect to the top element. The offset size of the vernier target (the horizontal distance between the two lines) was controlled by an adaptive staircase method (PEST, Taylor & Creelman, 1967).

Before the experiment, participants received some practice trials with the standard grating. With this standard grating, the individual duration of the vernier target was determined for each observer. The vernier duration was chosen such that a threshold of approximately 40 to 50″ was obtained (as durations, multiples of 5 or 6 ms were used). An auditory feedback signal provided feedback on incorrect responses. Participants were allowed a short break after all conditions were presented once.

After each stimulus presentation, the screen remained blank for 200 ms before the fixation screen for the next trial appeared. If participants did not respond within 3000 ms after stimulus offset, a beep sounded, and the trial was repeated at the end of the block.

2.6. Data analysis

By fitting a cumulative Gaussian to the data, thresholds (75% correct offset direction discriminations) were estimated for each block of 80 trials. A probit analysis was used to fit the cumulative Gaussian, assuming a guessing rate of 50%, and a percentage of motor errors equal to 2%. If the computed threshold was outside the range of presented offsets, the block was repeated.

In order to avoid extremely large offsets in a situation in which the target was invisible, we restricted the PEST-procedure to a maximum offset size of 300″. If a threshold below 300″ could not be reached, we recorded a value of 350″ (for details see Herzog et al., 2001).

3. Experiment 1

In the first experiment, we varied the number and position of longer lines within an otherwise homogeneous mask to compare the effects of local and global mask inhomogeneities.

3.1. Methods

Six observers (four students and the two authors) were presented with a sequence of a target vernier followed by one of seven possible masks (as depicted in the inset of Fig. 1b). The masks were created from the standard grating by increasing the length of some elements from 21′ to 41′ (two segments of each 20′ separated by a gap of 1′), as illustrated in Fig. 1a. In the ‘single element’ conditions, two longer lines were inserted in the standard grating on each side from the center. The distance of these two longer lines to the center was varied across conditions.

In the ‘multiple elements’ conditions, the number of longer lines was increased from one on each side of the vernier to six on each side. In the last mask of this set of conditions, every second element in the mask was 41′ long. The gratings are named after the locations of the longer elements relative to the center. For example, if the elements at position 1 and 3 from the vernier location are longer, the mask is referred to as ‘P1 + P3’. The mask for which every second element is longer, we term ‘Every Second’. All masks are symmetric around the center of the grating.

In each block of 80 trials, one mask was used. The order of the masks was varied across the six participants.

3.2. Results and discussion

Increasing the length of the two lines next to the vernier resulted in a strong increase of the masking strength (Fig. 1b, ‘P1’). When the longer lines were shifted away from the position of the target, significantly weaker masking was obtained ($F(3,15) = 9.85$, $p < 0.001$; white bars in the data plot). Pairwise comparisons revealed a significant difference between the P1 and the standard condition ($p < 0.01$), and between the P1 and the P3 condition ($p < 0.03$; marginally significant after Bonferroni correction), which suggests that lines close to the target affect its visibility more than lines further away.

The weaker masking with the single lines further away from the target can be explained from local interactions between the longer elements in the mask and the target. However, we also found a strong effect of the number of long lines. By adding even more long elements to the mask (which increases the overall intensity) a decrease in masking strength was obtained, yielding a level close to that of the standard grating if every second element was extended in length (black bars). The effect of the number of long elements was statistically significant (repeated measurements ANOVA comparing the four conditions: $F(3, 15) = 8.78$, $p < 0.01$). Pairwise comparisons revealed a significant difference between the P1 and the every second condition ($p < 0.01$), and between the P1 and the P1 + P3 condition ($p < 0.04$; marginally significant after Bonferroni correction). The effect of the number of longer lines shows that the masking strength can be reduced by increasing the intensity of the mask, which contrasts to typical findings in which masks with higher overall intensity yield stronger masking (Breitmeyer & Öğmen, 2006).

The differences between the corresponding thresholds of the 'single' and the 'multiple' conditions are small, suggesting that the outer long elements determine the strength of the mask, and not the elements neighboring the target. In a two-way repeated measure ANOVA, we tested the differences between the single and the multiple conditions. In this test, we left out the value of the P1 condition, since it was included in both the single and the multiple conditions, and only measured once for each observer. The ANOVA revealed a main effect of the distance of the outmost longer line ($F(2, 10) = 9.62$, $p < 0.01$), but no effect of the condition (single or multiple; $F(1, 5) = 1.61$, $p > 0.2$) and no interaction ($F(2, 10) = 0.25$, n.s.).

The small, non-significant difference between the masking strength in the 'single' and the 'multiple' conditions shows that the global layout and not the local structure of the mask around the target vernier determines the masking strength. All masks in the 'multiple' condition have the same local layout, that is, two long lines surrounding a normal length line (as in the 'P1' mask). The differences between the 'multiple' conditions can therefore not be the result of local contour interactions between the vernier target and the mask. Instead, we propose that the largest regular structure within each mask determines the masking strength. For the 'single' conditions, this largest structure is the set of normal length lines between the two longer lines. For the 'multiple' conditions, the largest regular structure in the neighborhood of the vernier is formed by the set of alternating long and short lines around the center. The widths of these regular structures are determined by the outmost long line. This explains why there is hardly any difference in masking strength between the 'single' and the 'multiple' conditions.

4. Experiment 2

In the first experiment, we showed that including two longer elements in a mask consisting of equal length lines can induce a strong increase in the masking strength if the longer elements are close to the target. However, if long elements are added in an alternating fashion, such as in the every second mask, the masking strength decreases to a level close to that of the standard grating. In Experiment 2, we show that it is not the number of longer lines *per se* that determines performance, but rather their regular arrangement.

4.1. Methods

4.1.1. Participants and procedure

Nine participants took part in Experiment 2. Except for the first author, none of the participants took part in the first experiment.

A vernier target was followed by one of six masks. The duration of the vernier was determined for each participant individually, such that performance for the standard grating was about 40–50″, while performance on the P1 grating was clearly below 350″. This last requirement was added with respect to Experiment 1, to allow for a comparison of strengths of the various masks, avoiding floor effects. Vernier durations ranged from 10 to 30 ms across participants.

4.1.2. Stimuli

The masks of Experiment 2 are illustrated in Fig. 2. Three of the masks ('standard', 'every second', and 'P1') were also used in Experiment 1. The three new masks have the same number of long (12) and normal length (13) lines as the every second mask. The center three elements of each mask (except for the standard grating) were identical: All masks had a normal length line in the center, surrounded by two longer lines. By using the same three center lines for all masks, we could make sure that any differences between the mask would be due to the global layout of the mask, and not due to local interactions of the lines neighboring the target vernier. The 'symmetric repetition' mask was used to test the importance of symmetry and repetition. It contains an alternation of two long and two short lines, and is mirror symmetric around the center. In

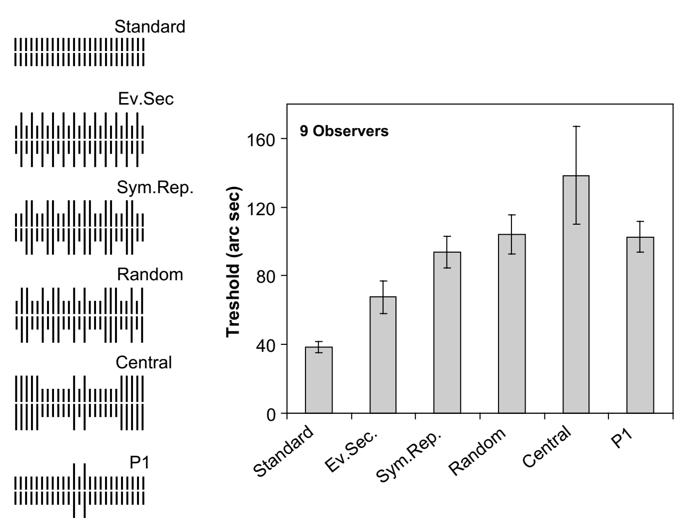

Fig. 2. Masks (left, in reverse contrast) and mean thresholds (right) from Experiment 2. Only a slight difference in thresholds was found between the 'symmetric repetition' and the 'random' mask. The data suggest that to obtain a weak mask, the structure needs to be very regular, such as in the 'every second' and the 'standard' condition. The lack of a significant difference in the thresholds of the 'P1' and the 'central' condition indicates that only the central elements of the mask are of importance to the masking strength. Error bars show the standard error of the mean. Please note the change of the ordinate with respect to Experiment 1.

contrast, the ‘random’ mask is asymmetric and it does not contain a clear repetition of elements. Finally, the ‘central’ mask tests whether the long lines need to be close to the vernier target to have an effect. The symmetric repetition mask had long lines at positions 3, 4, 7, 8, 11, 12, 14, 15, 18, 19, 22, and 23 (counted from left to right). The random mask’s longer lines were at positions 2, 3, 6, 8, 9, 12, 14, 18, 19, 20, 23, and 25. The central mask had double length lines at positions 1, 2, 3, 4, 5, 12, 14, 21, 22, 23, 24, and 25. The layout of the masks was kept constant across all 80 trials in a block.

4.2. Results and discussion

The right-hand side of Fig. 2 shows the mean thresholds across participants. For the three masks that we used in Experiment 1 (“Standard”, “Ev.Sec”, “P1”), we could replicate the pattern of results.

Compared to the ‘every second’ mask, thresholds rise when the twelve longer lines are distributed in a less regular fashion (“Sym. Rep.” and “Random”). No clear difference in the vernier offset discrimination threshold is found for these two conditions ($t(8) = 1.17$, $p > 0.2$, two-tailed). This result suggests that repetition and symmetry are not sufficient to create a weak mask. Only if the mask is very regular, such as in the ‘every second’ condition, the masking strength is reduced.

A comparison between the thresholds for the ‘central’ and the ‘P1’ mask did not reveal a significant difference ($t(8) = 1.16$, $p > 0.2$, two-tailed), although some small difference seems to be present between the two masks. This absence of a significant difference suggests that the more distant the lines from the center are, the weaker their effect is, which agrees with findings by Barlow and Reeves (1979), who found that dots near the axis of symmetry contribute more to the symmetry judgment than dots further away.

4.3. Regularity ratings

To determine how masking strength relates to a subjective measure of regularity, we asked 28 participants (lab members, colleagues, and relatives; none of whom had taken part in the experiments) to order the masks of Experiment 2 according to their regularity. Participants were asked to assign the value 1 to the mask they found most regular, whereas the value 6 was given to the mask which was judged to be most irregular. Masks were presented in black ink on white paper (no time constraints). Each participant received the masks in one of six possible randomly chosen orders. From the rank orders we computed the mean and the standard deviation, which provide an indication of the general trend in the ordering and of how much the orderings differed across the raters. Fig. 3 shows the mean ratings. Two masks stood out in the ratings: the standard mask was considered to be the most regular mask by most raters, the random mask the most irregular. Furthermore, the every second mask was often considered to be the second regular mask. Less pronounced differences were found for the remaining three masks (‘sym. rep’, ‘central’, and ‘P1’). The regularity ratings agree to a large extent with the masking data ($r = 0.82$). The main difference is that the masking data did not show clear differences between the ‘random’, the ‘symmetric repetition’, and the ‘P1’ and the ‘central’ mask, while the ratings did.

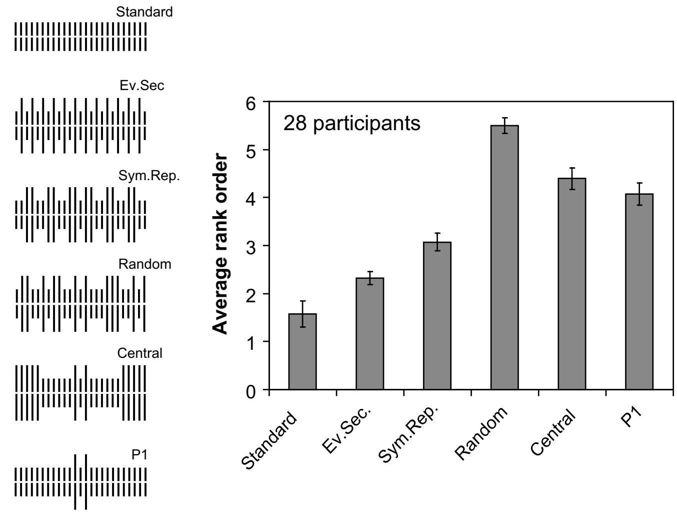

Fig. 3. Average rank order assigned to each of the six masks used in Experiment 2 (right panel). Left, illustration of the stimuli (in reverse contrast). Error bars show the standard error of the mean.

5. Experiment 3

In Experiment 3, we determined whether the effect of increasing the length of two lines of an otherwise regular mask only occurs when the mask in itself is extremely regular. Therefore, we increased the length of two lines of the every second mask, which is slightly less regular than the standard mask. Furthermore, we investigated whether a *decrease* of the length of two lines has the same effect as an increase of the length. If decreasing the length results in the same increase in masking strength as increasing the length, this provides another confirmation of our hypothesis derived from Experiment 2 that mask regularity rather than overall mask intensity or local contour interactions between neighboring lines determine the masking strength.

5.1. Methods

5.1.1. Participants and procedure

Seven participants took part in Experiment 3. Four of them also participated in Experiment 2. Vernier durations ranged from 10 to 25 ms, which allowed for a comparison of the thresholds of relatively strong masks (with shorter vernier presentation durations, the vernier would be masked completely for all masks except the ‘standard’ and the ‘every second mask’).

5.1.2. Stimuli

Fig. 4 (left panel) illustrates the masks of Experiment 3, which includes three masks that were also used in Experiments 1 and 2 (‘standard’, ‘every second’, and ‘P1’). The three new masks were constructed from the every second mask. The ‘short’ mask has elements with segments of half the standard length (5′) at position 1 from the vernier. The ‘long’ mask has elements with segments which are twice as long (40′) as the longer (20′) elements normally at position 1 of the every second mask. The ‘gap’ mask is similar to the ‘long’ mask, but the 20′ extensions were shifted 5′ up and downwards.

5.2. Results and discussion

Fig. 4 (right panel) shows the mean thresholds for each of the masks in Experiment 3. As in Experiments 1 and 2, weakest masking was found for the standard grating, slightly increased masking for the every second mask, and stronger masking for the P1 mask.

With the every second mask as the base mask, an additional increase of the length of the lines at the P1 position (‘Long’) yielded a strong increase in the threshold ($t(6) = 6.45$, $p < 0.001$). One could argue that this increase was due to the increase of the overall intensity of the mask and not because of the change of the mask’s regularity. However, an even stronger increase in threshold is found (marginally significant from the ‘Long’ condition; $t(6) = 1.90$, $p = 0.052$) when the lines at the P1 position are made shorter (‘Short’) instead of longer. This suggests that the reduced regularity of the mask rather than the increased overall mask intensity caused the increase in the masking strength. In addition, this finding argues against local interactions between the mask’s center lines and the vernier.

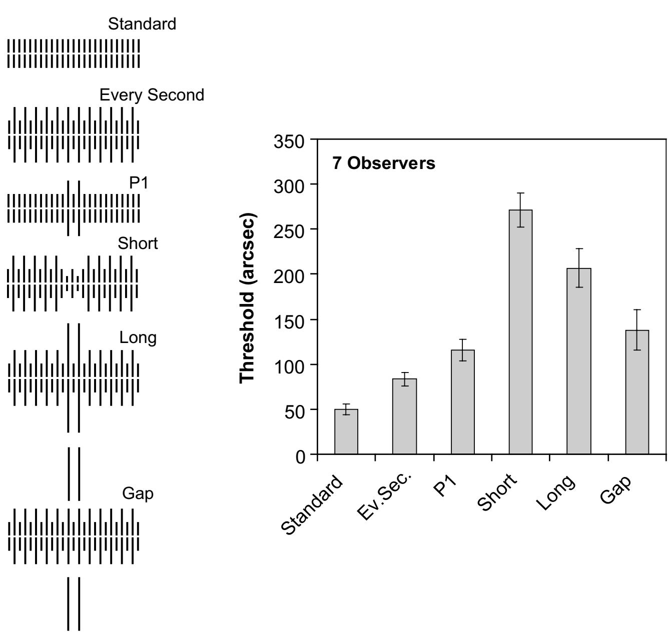

Fig. 4. Masks (left, in reverse contrast) and mean thresholds (right) from Experiment 3. As before, weakest masking is found for the ‘standard’ mask, slightly increased masking for the ‘every second’ mask, and stronger masking for the ‘P1’ mask. If either a shorter or a longer element is added to position 1 from the vernier in the ‘every second’ mask, the masking strength strongly increases. By inserting a gap in the long elements (‘Gap’) at position 1, the masking strength is reduced compared to the long condition. We suggest that the gap induces a grouping of the grating into an ‘every second’ mask and four contextual elements. Error bars show the standard error of the mean.

The thresholds for the ‘Gap’ mask are lower than those for the ‘Long’ mask ($t(6) = 3.94$, $p < 0.01$), suggesting that the gap resulted in a grouping of the grating into an ‘every second’ grating and four contextual lines.

6. General discussion

In three experiments, we investigated the effect of the global layout of a visual backward mask. We found that the global structure of the mask has a profound effect on its masking strength. More specifically, our findings suggest that the *global regularity* of the mask’s layout determines its effect on the target. Extending the length of two elements near the center of the mask dramatically impairs offset discrimination of the vernier target (‘P1 mask’, Fig. 1). However, extending the length of more lines in a regular fashion reduces the masking strength to a level close to that of a mask without extended lines (‘Standard’, Fig. 1) if every second line is extended (‘Every Second’, Fig. 1). Thresholds are similar when more long lines are added to the mask or when the two long lines are shifted away from the target position, suggesting that the outmost long elements determine the masking strength and not the elements closest to the vernier. The effects of Experiment 1 cannot be explained by the sheer number of longer elements in the mask, because less regular arrangements of the longer elements result in strong decreases in performance (Experiment 2; Fig. 2). Instead, the results suggest that the regularity of the mask determines its masking strength.

Effects of mask regularity have been shown before (Coltheart & Arthur, 1972). A random dot pattern is a much stronger mask than the same dots arranged in a regular pattern. However, this effect could have arisen from local target-mask interactions, as well as the overall structure of the mask. Here, we have shown it is not just the mask elements close to the target that determine the masking strength, but the entire mask’s layout. For many existing models of masking this finding might pose a problem, because most models only take local interactions into account.

Masking strength increases, not only when the structure of a very regular mask is broken, but also when the structure of a slightly less regular mask (the ‘every second’ mask) is changed (Experiment 3; Fig. 4, ‘Long’ and ‘Short’). These increases in masking strength are not due to the increased intensity of the mask: both an increase and a reduction of the length of two of the elements result in a similar impairment of performance on the target. However, the effect of the extension of two lines can be partially reversed when the connectedness of the extensions is manipulated. By inserting a small gap between the line extensions and the remainder of the mask, the masking strength is significantly reduced

(Fig. 4, 'Gap'). This result can be interpreted as evidence for a different grouping of the mask's elements, although the increased distance of the extended elements from the target might play a role too.

The condition in which the line length was reduced ('short') instead of extended (Fig. 4) imposes strong constraints on explanations based solely on lateral inhibition (both static and dynamic models, e.g. Herzog, Ernst, Etzold, & Eurich, 2003) or surround suppression, as well as on mechanisms based on the overall intensity (luminance × surface × duration) of the stimulus (Breitmeyer & Öğmen, 2006 p. 48). These models and explanations all predict that the mask with the shorter lines ('Short') should produce weaker masking than that with longer lines ('Long'), while the experimentally obtained thresholds were similar for the two masks.

It might be hypothesized that, for example, by adding long lines (as in the 'P1' mask), the Fourier spectrum of the mask image strongly changes. This may activate additional (or other) spatial frequency channels that overlap with the channels triggered by the vernier target, which will lead to stronger masking (Weisstein, Harris, Berbaum, Tangney, & Williams, 1977). However, Fig. 5b (masks ii and iii) shows that the spectrum hardly changes by adding two long lines. Moreover, a relatively large change in the amplitude spectrum of the mask can also go together with just a very small change in the masking strength (Fig. 5b, i and ii). These results together show a double dissociation between performance and spectrum similarity. This indicates that visually inspecting the amplitude spectrum of the mask does not provide accurate predictions for the masking strength. One may argue, however, that instead of the amplitude spectrum, the phase spectrum is of importance to the masking strength (Caelli & Moraglia, 1987). Fig. 5c shows that also the phase spectrum is not a good predictor of the masking strength. Two masks with relatively similar phase spectra can have different masking strengths (e.g., masks ii and iv). In addition, masks can have dissimilar phase spectra, but similar masking strengths (masks i–ii, and iii–iv). Together, these observations show that the masking strength does not follow directly from the amplitude or the phase spectrum. However, this does not exclude that more sophisticated computations from the Fourier spectra do provide a good explanation of the masking results.

Low-pass filtering does not seem to be able to explain our results either. A low-pass filter may strongly blur the inside of the mask which leaves only the envelope of the mask to interact with the target vernier. Such outer edge interactions can not explain why shorter lines next to the vernier target yield stronger masking than longer lines ('Short' vs 'Long' in Fig. 4). In addition, the nearest edges of the P1 and the every second mask of Experiment 1 are at the same distance, however the two masks differ clearly in masking strength (Fig. 1).

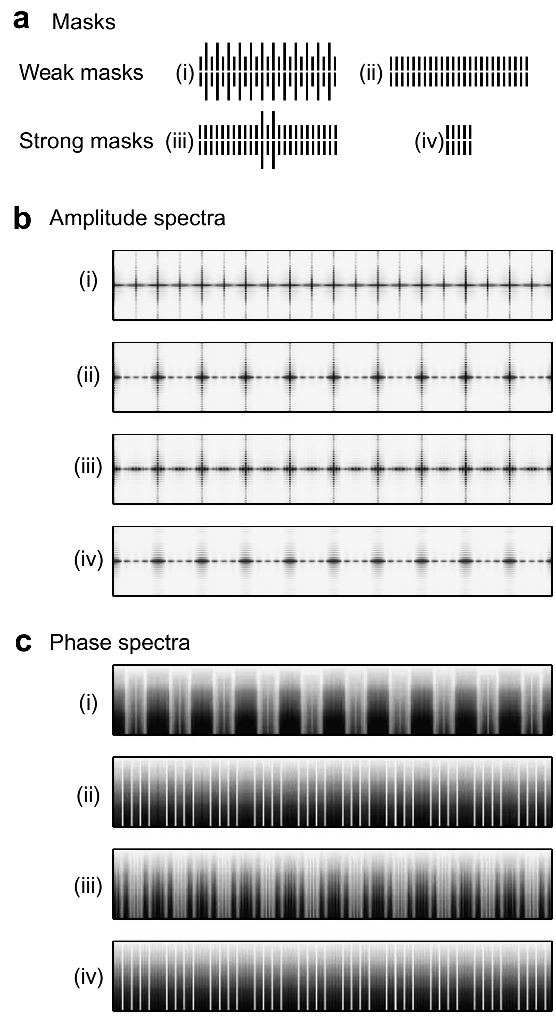

Fig. 5. Amplitude (b) and phase (c) spectra for four masks (a). Two of these masks yield weak masking (i, ii), and two strong masking (iii, iv). The fourth mask (iv) was taken from a different study (Herzog et al., 2001). Masks with different amplitude spectra or phase spectra can have similar masking strengths, whereas masks with similar spectra can differ strongly in masking strength, suggesting that our findings do not follow directly from the Fourier spectra of the masks.

6.1. Theories of visual regularities

The masking strengths of the masks in Experiment 2 showed a clear correlation with the subjective ratings of their visual regularity ($r = 0.82$). This correlation suggests that theories of visual regularity should also be able to account for our masking results. However, it seems that they have problems explaining the masking strength of some of the masks. Almost all regularity theories cannot explain that an asymmetric (the 'random' mask from Experiment 2) does not yield significantly stronger masking than a symmetric mask that also includes a repeated pattern (the 'symmetric repetition' mask from Experiment 2). For example, in structural information theory (SIT, Van Der Helm & Leeuwenberg, 1991, 1996), the random mask can be described as the following sequence of a's and b's (a, short line; b, long line): 'abbaababbaababaaabbbaabab'. The shortest description of this pattern has a complexity of 9, which is much higher than the complexity of the 'symmetric repetition' mask, which is only 4.[1] Similarly, minimal model theory (Feldman, 1977, 1999, 2003), in which the number of layers in the parse tree describing the stimulus relates to the complexity of the stimulus, predicts a higher complexity for the random mask than for the 'symmetric repetition' mask. This means that the complexity from this theory cannot be used to predict the masking strength.

For the transformational theory (e.g. Garner, 1970), which takes the number of transformations (e.g., translations, rotations) a stimulus can undergo without changing shape as a measure of complexity, the findings of Experiment 3 pose an additional problem. All masks allow for a similar amount of rotations and reflections without changing the pattern. However, the masking strength clearly differed across the masks.

6.2. Constructing a mask

Finally, let us consider what our results mean to the researcher who uses masking as a tool. Our results provide an indication as to how to construct a strong mask (see also Haber, 1970). We suggest that to build a strong mask, one should start with a mask consisting of elements that are similar to the target. In this mask, a few elements should be changed such that the regular arrangement of mask elements is broken. Once the mask's structure is set, its strength can be increased by increasing the mask's duration.

References

Alpern, M. (1953). Metacontrast. *Journal of the Optical Society of America, 43*(8), 648–657.

Bach, M. (1996). The "Freiburg visual acuity test". Automatic measurement of visual acuity. *Optometry and Vision Science, 73*, 49–53.

Barlow, H. B., & Reeves, B. C. (1979). The versatility and absolute efficiency of detecting mirror symmetry in random dot displays. *Vision Research, 19*(7), 783–793.

Breitmeyer, B. G., & Öğmen, H. (2006). *Visual masking: Time slices through conscious and unconscious vision*. New York: Oxford University Press.

Bridgeman, B., & Leff, S. (1979). Interaction of stimulus size and retinal eccentricity in metacontrast masking. *Journal of Experimental Psychology: Human Perception and Performance, 5*(1), 101–109.

Caelli, T., & Moraglia, G. (1987). The concept of spatial frequency channels cannot explain some visual masking effects. *Human Neurobiology, 6*(1), 63–65.

Coltheart, M., & Arthur, B. (1972). Evidence for an integration theory of visual masking. *Quarterly Journal of Experimental Psychology, 24*(3), 262–269.

Feldman, J. (1977). Regularity-based perceptual grouping. *Computational Intelligence, 13*(4), 582–623.

Feldman, J. (1999). The role of objects in perceptual grouping. *Acta Psychologica, 102*, 137–163.

Feldman, J. (2003). What is a visual object? *Trends in Cognitive Sciences, 7*(6), 252–255.

Garner, W. (1970). Good patterns have few alternatives. *American Scientist, 58*, 34–42.

Growney, R. (1977). Metacontrast as a function of spatial separation with narrow line targets and masks. *Vision Research, 17*(10), 1205–1210.

Haber, R. (1970). Note on how to choose a visual noise mask. *Psychological Bulletin, 74*(5), 373–376.

Herzog, M. H., Dependahl, S., Schmonsees, U., & Fahle, M. (2004). Valences in contextual vision. *Vision Research, 44*, 3131–3143.

Herzog, M. H., Ernst, U., Etzold, A., & Eurich, C. (2003). Local interactions in neural networks explain global effects in the masking of visual stimuli. *Neural Computation, 15*, 2091–2113.

Herzog, M. H., & Fahle, M. (2002). Effects of grouping in contextual modulation. *Nature, 415*, 433–436.

Herzog, M. H., Fahle, M., & Koch, C. (2001). Spatial aspects of object formation revealed by a new illusion, shine-through. *Vision Research, 41*, 2325–2335.

Herzog, M. H., Harms, M., Ernst, U., Eurich, C., Mahmud, S., & Fahle, M. (2003). Extending the shine-through effect to classical masking paradigms. *Vision Research, 43*, 2659–2667.

Herzog, M. H., & Koch, C. (2001). Seeing properties of an invisible object: Feature inheritance and shine-through. *Proceedings of the National Academy for Science, USA, 98*, 4271–4275.

Herzog, M. H., Schmonsees, U., & Fahle, M. (2003). Collinear contextual suppression. *Vision Research, 43*, 2915–2925.

Kolers, P. A. (1962). Intensity and contour effects in visual masking. *Vision Research, 2*(9–10), 277–280.

Ramachandran, V. S., & Cobb, S. (1995). Visual attention modulates metacontrast masking. *Nature, 373*, 66–68.

Sturr, J. F., & Frumkes, T. E. (1968). Spatial factors in masking with black and white targets. *Perception and Psychophysics, 4*, 282–284.

Sturr, J. F., Frumkes, T. E., & Veneruso, D. M. (1965). Spatial determinants of visual masking: Effects of mask size and retinal position. *Psychonomic Science, 3*, 327–328.

Taylor, M. M., & Creelman, C. D. (1967). PEST: Efficient estimates on probability functions. *Journal of the Acoustical Society of America, 41*, 782–787.

Van Der Helm, P. A., & Leeuwenberg, E. L. J. (1991). Accessibility, a criterion for regularity and hierarchy in visual pattern codes. *Journal of Mathematical Psychology, 35*, 151–213.

Van Der Helm, P. A., & Leeuwenberg, E. L. J. (1996). Goodness of visual regularities: A nontransformational approach. *Psychological Review, 103*, 429–456.

Wehrhahn, C., Li, W., & Westheimer, G. (1996). Patterns that impair discrimination of line orientation in human vision. *Perception, 25*, 1053–1064.

Weisstein, N., Harris, C. S., Berbaum, K., Tangney, J., & Williams, A. (1977). Contrast reduction by small localized stimuli: Extensive spatial spread of above-threshold orientation-selective masking. *Vision Research, 17*(3), 341–350.

Werner, H. (1935). Studies on contour: I. Quantitative analysis. *American Journal of Psychology, 47*, 40–64.

Williams, M. C., & Weisstein, N. (1981). Spatial frequency response and perceived depth in the time-course of object superiority. *Vision Research, 21*(5), 631–646.

Williams, M. C., & Weisstein, N. (1984). The effect of perceived depth and connectedness on metacontrast functions. *Vision Research, 24*(10), 1279–1288.

[1] We thank Peter van der Helm for computing these values for us.